Nuclear and Particle Astrophysics at CIPANP 2003

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Abstract. In the nuclear and particle astrophysics session of CIPANP 2003 we heard talks on a number of topics, focused for the most part into four broad areas. Here we outline the discussions of the standard cosmological model, dark matter searches, cosmic rays, and neutrino astrophysics. The robustness of theoretical and experimental programs in all of these areas is very encouraging, and we expect to have many questions answered, and new ones asked, in time for CIPANP 2006.

1. THE STANDARD COSMOLOGY

In recent months the WMAP satellite has provided the clearest picture of temperature fluctuations in cosmic microwave background (CMB) to date [1]. The power spectrum of these fluctuations is a sensitive function of the cosmological parameters, such as the total energy density, matter density, baryon density, Hubble constant and others. The emerging model was convincingly confirmed: the universe is spatially flat, consisting mostly of “dark energy” that behaves like a cosmological constant, about 23% dark matter, and about 4% baryons. The sum of the neutrino masses is limited to be less than 0.7 eV, much more strict than the bound from terrestrial laboratories. The Compton scattering optical depth implies an early reionization at redshift ~ 17. These results will improve, as the WMAP team plans to take at least 4 years of data.

Several profound questions arise from these results. To start, the nature of the dark matter and the dark energy are completely unknown. We understand the 4% in baryons, but the other 96% is a mystery. Furthermore, there is an indication of a deficit of power on the largest scales (in e.g. the quadrupole and octupole moments), but the meaning of this unclear. A finite universe is one among many unlikely possibilities.

The SNAP satellite[2] has been proposed to study the nature of the dark energy by measuring the Hubble diagram (redshift – distance relation) using type Ia supernovae (SNIa) as standard candles, as has been done from the ground. Ground based measurements of this kind have already shown that there is a large density of dark energy. The SNAP team hopes to study the equation of state $w: \ (p = w\rho)$ of this material. A satellite is required to significantly extend the ground–based results, as a large number of SNIa with redshifts $z > 1$ is required: this tests the universe in its decelerating phase. The wavelengths of interest are redshifted into the infrared, thus the necessity of a space–based instrument. Furthermore, the exact nature of the progenitors of SNIa is unknown. A large sample can be split into many subsamples to study systematic effects. SNAP is

fundamentally a large survey telescope, and should have a broad science reach.

Big Bang Nucleosynthesis (BBN)[3] tries to explain the primordial abundances of light elements, in particular the stable isotopes of hydrogen, helium and lithium. As a function of only the baryon to photon ratio, these abundances can be calculated by tracking the network of nuclear reactions in the hot big bang. The primordial abundance of deuterium depends sensitively on the one free parameter, thus deuterium measurements can provide an accurate assessment of the cosmological baryon density. Lyman-α clouds obscuring distant quasars presumably consist of predominantly unprocessed gas, and thus reflect primordial abundances. With the right column depth of hydrogen (not so small that deuterium is unobservable, and not so large so that the damping wings of hydrogen cover the deuterium line), the primordial deuterium abundance is measured. At present, the implied baryon density is fully consistent with the WMAP value, with comparable errors. To go further, many more such systems would be needed. Suitable systems are currently found at the rate of one per year, so for now progress on the baryon density will come from CMB measurements.

Cosmological observations have the potential to probe Planck-scale physics[4]. Inflationary theories usually predict that observable wavelengths (e.g. galaxy and cluster scales) originated during inflation as sub-Planck fluctuations. Thus, inflation can in principle probe quantum theories of gravity such as superstring theory. With not overly optimistic assumptions, a 1% modulation of the CMB fluctuations might be produced by Planck-scale physics during inflation, detectable in the next decade or two.

2. DARK MATTER SEARCHES

The Standard Cosmological Model requires that 23% of the energy density in the universe is some form of non–baryonic nearly collisionless clustering matter. A new stable particle would fit the bill, as has been known for several decades. In this regard the dark matter problem is more tractable than the dark energy problem — dark matter “looks like” something we understand, while dark energy is completely mysterious.

Two possible candidates for dark matter have survived numerous tests and remain viable. The first is the lightest superpartner in supersymmetric extensions to the Standard Model, which is naturally stable, weakly interacting, and electrically neutral. The second is the axion, arising in a compelling solution to the strong CP problem.

Weakly Interacting Massive Particles (WIMPs), such as those in supersymmetric models can be detected in sensitive low–background experiments by their rare scattering from atomic nuclei. The nuclear recoil deposits energy, which in principle is detectable. Two such detectors currently running are CDMS and DAMA.

CDMS[5] uses germanium and silicon detectors. These are sensitive to both phonons and ionization. The ratio of these two signals powerfully discriminates against background, as nuclear recoils exhibit much lower ionization that most backgrounds (electrons and gamma rays). CDMS-I ran in a shallow site at Stanford, and the final WIMP exclusion results are now available. CDMS-II is currently running in the Soudan mine, with new results anticipated by the end of 2003.

The DAMA[6] detector uses NaI scintillators. They do not have the background

rejection capabilities of CDMS, but instead rely on the annual modulation of the WIMP signal: as the Earth orbits the Sun, its relative velocity with respect to the WIMP "wind" is modulated by several tens of km s^{-1}, leaving a rate modulation of a few percent. In the 4-year data such a modulation is seen, though the implied mass and cross section are nearly ruled out by other experiments (CDMS, EDELWEISS, ZEPLIN). Three more years of data have been released since the conference, and the modulation signal is strengthened. Furthermore, the successor experiment LIBRA is being installed now.

The future of WIMP searches requires that ton-scale detectors be constructed. The XENON proposal[7] to use a two-phase detector for both scintillation light and ionization is a promising possibility for scalability to a one ton target mass. Background can again be rejected by the lower levels of ionization from nuclear recoils relative to electronic processes. Small prototypes are currently being tested. The construction of a 10 kg prototype is well underway. The goal is to build a 100 kg module; with this a ton-scale detector could feasibly be built in the next decade.

Axions in the range micro- to milli-eV remain a viable dark matter candidate. They require a vastly different experimental approach: conversion to microwave photons in a magnetic field. These photons are then detected with with what is essentially a very sensitive radio receiver. The axion dark matter experiment ADMX is ongoing, already scanning deep in the allowed model range[8]. Upgraded receivers using SQUID amplifiers are on the way. As light pseudoscalars, axions have a bounded parameter space, as their interactions are essentially the same as neutral pions. The lowest allowed axion-photon couplings are within reach.

3. COSMIC RAYS

Energetic cosmic ray nuclei are an important probe of high energy processes in astrophysics[9]. Supernova blast waves are capable of accelerating protons to energies of 10^{15} eV, the "knee" in the spectrum where the power law shifts to a steeper value. Very puzzling are the ultra high energy cosmic rays with energies in excess of 10^{20} eV. Various acceleration mechanisms have been proposed, involving FR II galaxies, interacting galaxies, jets in radio sources (with Lorentz factor 10), gamma ray bursts (with Lorentz factor 300), and others. Top-down models have also been considered: UHECRs may arise in the decay chains of supermassive particles. Whichever mechanism produces UHECRs, they must originate cosmologically nearby, within roughly 100 Mpc. The GZK cutoff operates for nuclei above 10^{20} eV / A, where the threshold for pion photoproduction on the CMB is exceeded. UHE photons have a similar cutoff at lower energy, at the pair production threshold. The nature of the observed events above 10^{20} eV is unknown, and difficult to determine experimentally. Nuclei such as iron, protons, photons, and neutrinos are all possibilities.

The experimental situation in UHECRs is quite promising. The HiRes experiment[10] consists of two air fluorescence detectors situated 12.6 km apart, allowing stereoscopic viewing of the air showers induced in the atmosphere. The dataset exhibits the GZK cutoff, though at low significance. The data are in agreement with AGASA, the Japanese particle detector, and the AGASA data does not exhibit the cutoff. The rela-

tive calibration between air fluorescence and particle detectors is uncertain; the FLASH collaboration[11] at SLAC expects to measure this to better than 10% accuracy. HiRes does not see the clustering visible in the AGASA data, though again the experiments are consistent. This of course dilutes the AGASA evidence for clustering. The collaboration expects three more years of data to be taken, which may clear up the situation.

The plan for the Pierre Auger project[12] is to use both particle detectors (with 100% duty cycle) and air fluorescence detectors (with 10% duty cycle). The project promises greatly enhanced statistics and cross-correlation between the two methods. Two sites are planned: one in Argentina to be fully operational in 2004, and one in the northern hemisphere. 3000 events per year per site above 10^{19} eV are expected, with 30 per year per site above 10^{20} eV. The comparison of the two detector types will allow more accurate energy measurements, and furthermore the identification of the primary will be more certain (e.g. proton vs. Fe). At the southern site, a mountain range will act as a neutrino converter for low altitude primaries, so UHE neutrinos can be studied as well.

At energies below 1 TeV, the Alpha Magnetic Spectrometer (AMS)[13] will measure the spectra of cosmic ray species with higher accuracy that has been possible. Of particular interest are several exotic possibilities, including antinuclei, dark matter, and quark matter "strangelets". AMS-01, which flew on the space shuttle, placed limits on the antihelium to helium ratio of 10^{-6}. AMS-02 will be installed on the international space station as early as 2005. With three years of data, the sensitivity to antihelium will be improved to 10^{-9}. AMS is sensitive to dark matter since annihilations in the galactic halo may produce anomalous levels of antiprotons and positrons at low to moderate energies, though very low energy particles are difficult to study because of the geomagnetic cutoff. AMS will have some sensitivity to photons in the sub-TeV range as well. A final possibility is the search for stable strangelets. They would be easily identified by their anomalous charge to mass ratios. Overall, AMS is a high statistics cosmic ray experiment, and will advance our knowledge considerably.

4. NEUTRINO ASTROPHYSICS

The advent of large neutrino telescopes is exciting for high energy astrophysics. AGNs, GRBs, microquasars, and dark matter annihilations are all interesting possible sources of neutrinos at GeV energies and higher.

The AMANDA array[14] at the south pole uses strings of photomultipliers (PMTs) deep in the ice to detect the tracks from (primarily muon) neutrinos. At 200m in diameter and 400m tall, it detects about 4 neutrinos per day, primarily atmospheric. From the 2000 dataset, no point sources were detected, but the photon flux limit was reached (based on the expected relationship between photon and neutrino fluxes from hadronic processes). With timing information, GRBs are within a single order of magnitude of detectability. Over the next decade, AMANDA will be upgraded to IceCube, with 80 strings totaling 4800 PMTs, with an effective volume of a cubic km. Neutrino energies from 50 GeV to more than a PeV will be studied. At high enough energies, the three neutrino flavors can be disentangled: electron from the shower characteristics, and tau from the "double bang" signature of the the recoil track and subsequent decay. IceCube will be installed

starting in 2004, with completion expected in 2010.

ANTARES[15] is a complementary neutrino telescope to be built at the floor of the Mediterranean. 12 cables totaling 1000 PMTs will cover 0.1 km^2, spaced at intervals of 60m. Seawater has a longer scattering length but a shorter absorption length than ice. Thus, the PMTs must be closer together, but the angular resolution is superior: above 10 TeV, a resolution of 0.2° is expected. Between AMANDA / IceCube and ANTARES, most of the sky will be covered. One string is currently running, and completion is planned for 2005. The design for a km^3 upgrade is also underway.

The Super Kamiokande[16] neutrino detector has also begun to do extra-solar neutrino astronomy. A search for the diffuse neutrino background from supernovae has been performed, and interesting limits have already been set.

5. FUTURE OUTLOOK

The future of nuclear and particle astrophysics looks bright. We have a Standard Cosmological Model, but we understand very little about its matter and energy contents. We have observed very high energy processes, beyond the reach of terrestrial accelerators, but the results are puzzling. Several programs of extra-solar neutrino astronomy are underway. The level of experimental activity is very encouraging. We fully expect many new and interesting results to be reported at CIPANP 2006.

ACKNOWLEDGMENTS

We thank all of the speakers in the nuclear and particle astrophysics session of CIPANP 2003 for such interesting and informative talks, and we thank the organizers for putting on such a good conference.

REFERENCES

1. Spergel, D. N. et al., Astrophys. J., in press (2003).
2. `http://snap.lbl.gov`
3. Burles, S., Nollett, K. M., & Turner, M. S., Astrophys. J. Lett. **552**, L1 (2001).
4. Easther, R., Greene, B. R., Kinney W. H., and Shiu, G., Phys. Rev. D **64**, 103502 (2001).
5. Akerib, D. S., et al., `hep-ex/0306001`
6. Bernabei R., et al. Phys. Lett. B **480**, 23 (2000); Bernabei R., et al. Riv. N. Cim. **26**, 1 (2003).
7. Aprile, E., et al., `astro-ph/0207670`
8. Asztalos, S. J., et al., Astrophys. J. **571**, L27 (2002).
9. Gaisser, T. K., and Stanev, T., “Cosmic Rays,” Phys. Rev. D **66**, 010001 (2002).
10. Abu-Zayyad, T., et al., `astro-ph/0208301`
11. `http://www.slac.stanford.edu/grp/rd/epac/Meeting/200211/sokolsky.pdf`
12. `http://www.auger.org`
13. `http://ams.cern.ch/AMS/ams_homepage.html`
14. `http://amanda.uci.edu`
15. `http://antares.in2p3.fr`
16. Malek, M., et al., Phys. Rev. Lett. **90**, 061101 (2003).